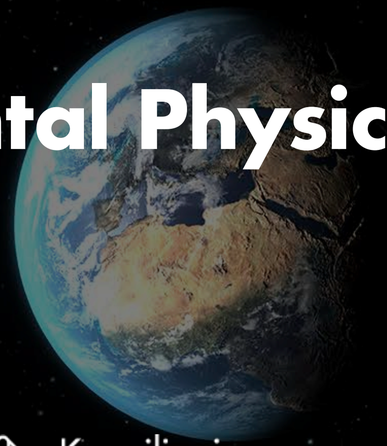
Seminar "Discovering the Universe from Estonia"
Tallinn 2024

LISA mission:
Gravitational Waves as the key to Fundamental Physics



Hardi Veermäe
KBFI

January 11, 2024

Keemilise ja Bioloogilise Füüsika Instituut
National Institute of Chemical Physics and Biophysics

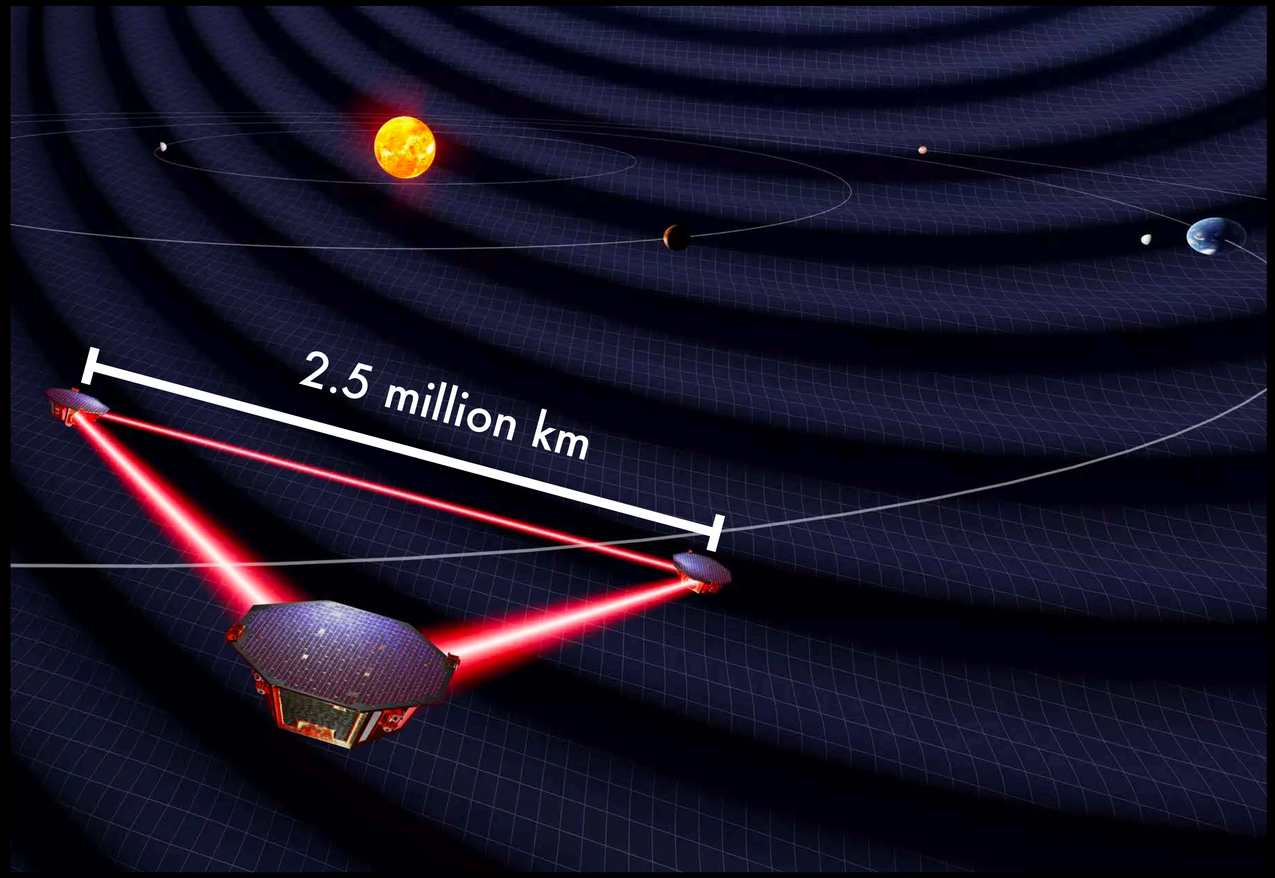
who are we?

laboratory of ***High Energy and Computational Physics***
of the ***National Institute for Chemical Physics and Biophysics***

- topics: *particle physics, cosmology and fundamental physics and gravitational wave physics, data analyses on grid and cloud systems, computational material science*
- 26 researchers (incl. postdocs), 8 PhD students
- leading partner in the Center of Excellence
  - “Dark Side of the Universe” (2016-2023)
  - “Foundations of the Universe” (2024-2030)
- partner in Estonian Scientific Computing Infrastructure (ETAIS)
- members of Estonian CERN and ESA scientific consortia
- one of the leading research groups in high energy physics in northern Europe and the only one in the Baltics

LISA
Laser Interferometer Space Antenna

- first gravitational wave observatory in space
- planned launch in *2037*
- *4+6* years of operation
  4 years with a possible 6 year extension
- consists of *3 spacecraft*
- *50 million km behind Earth* in a heliocentric orbit
- tech demonstration: *LISA pathfinder* (2015-2017)
- L class mission



Gravitational Waves

a very brief history of gravitational waves

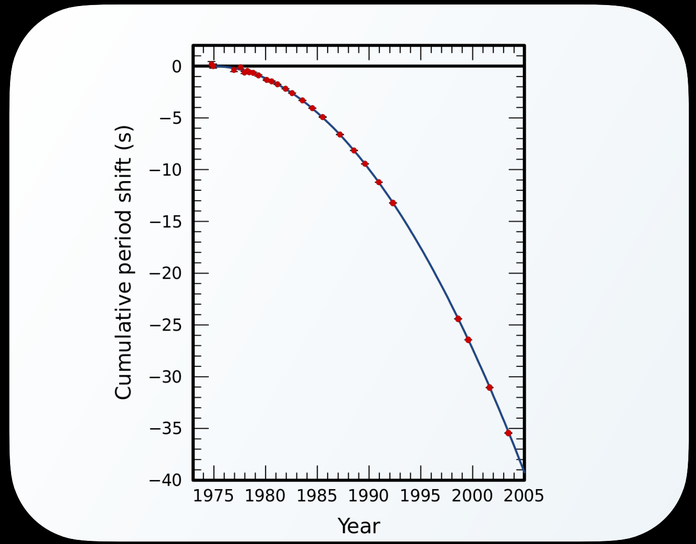
20TH CENTURY

1916: GWs predicted by Einstein

theoretical status uncertain until the second half of the 20th century

1970s: first indirect observation of GWs

orbital decay of the Hulse-Taylor binary pulsar



21ST CENTURY

2015: first direct detection of GWs

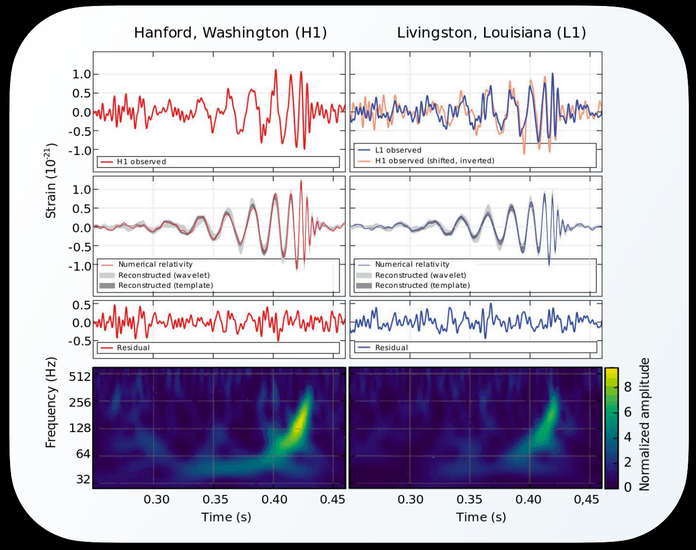
GW150914 - merger of $\mathcal{O}(30)$ solar mass BHs [LIGO]

2017: first merger of neutron stars

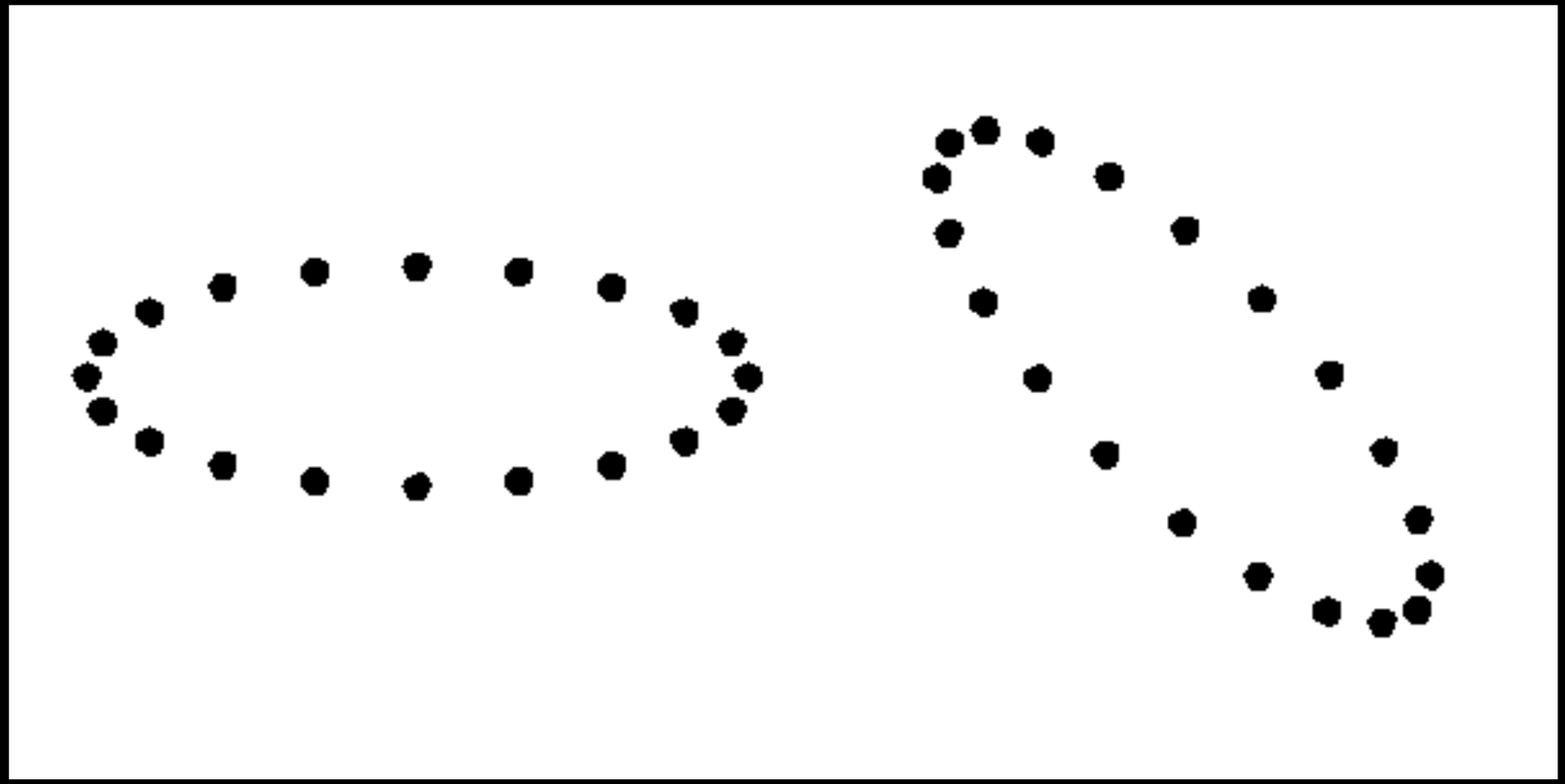
GW 170817

2023: first evidence for a GW background

pulsar timing array experiments [NANOGrav]



how to detect gravitational waves?

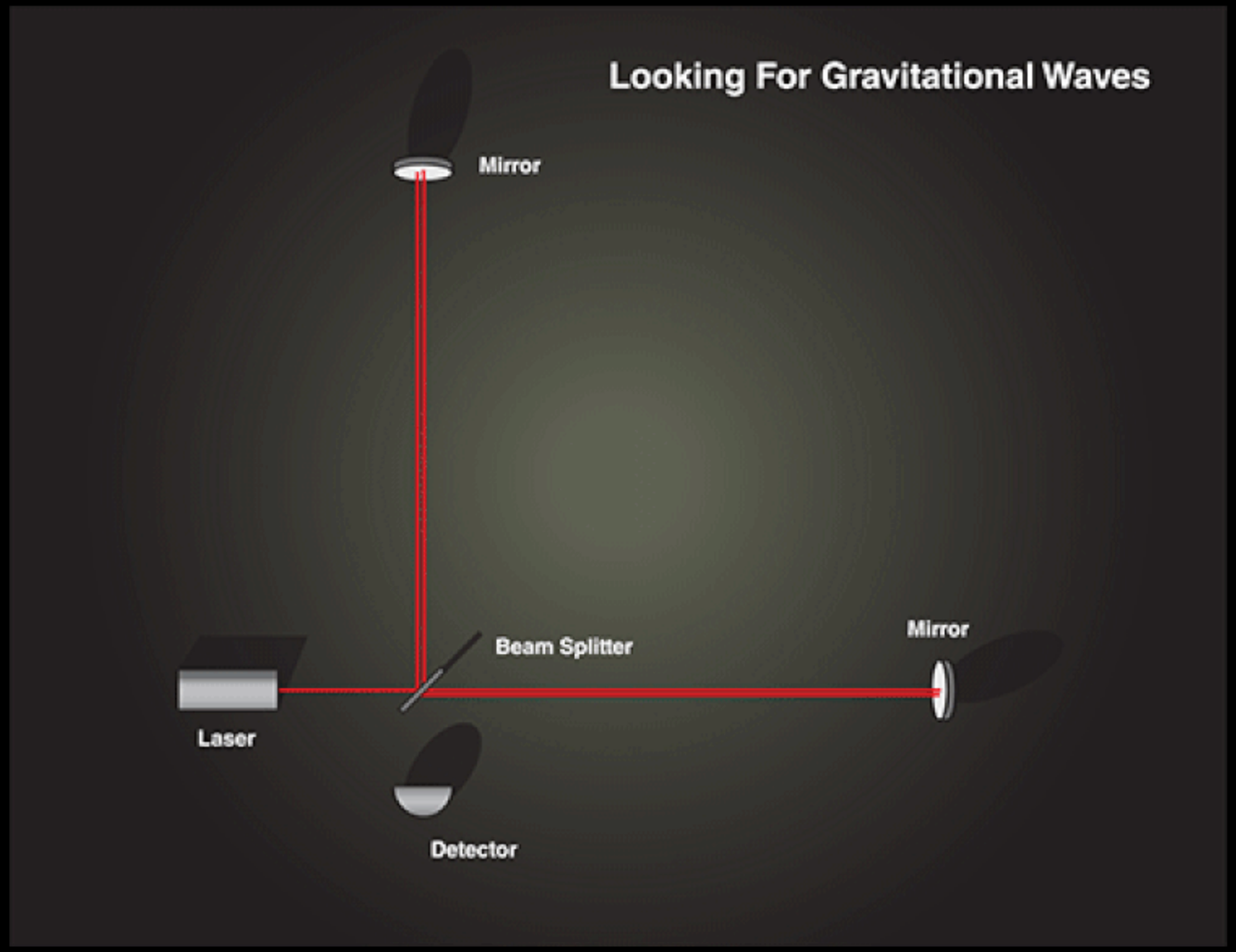


two polarization states:

\+ polarization

x polarization

how to detect gravitational waves?



GRAVITATIONAL WAVES MODULATE LEG LENGTHS

$$\Delta L = \Delta L_x - \Delta L_y = h_+ L_0 cos(\omega t)$$

gravitational wave amplitude: $h \approx 10^{-22}$

leg length: $L = 4km$

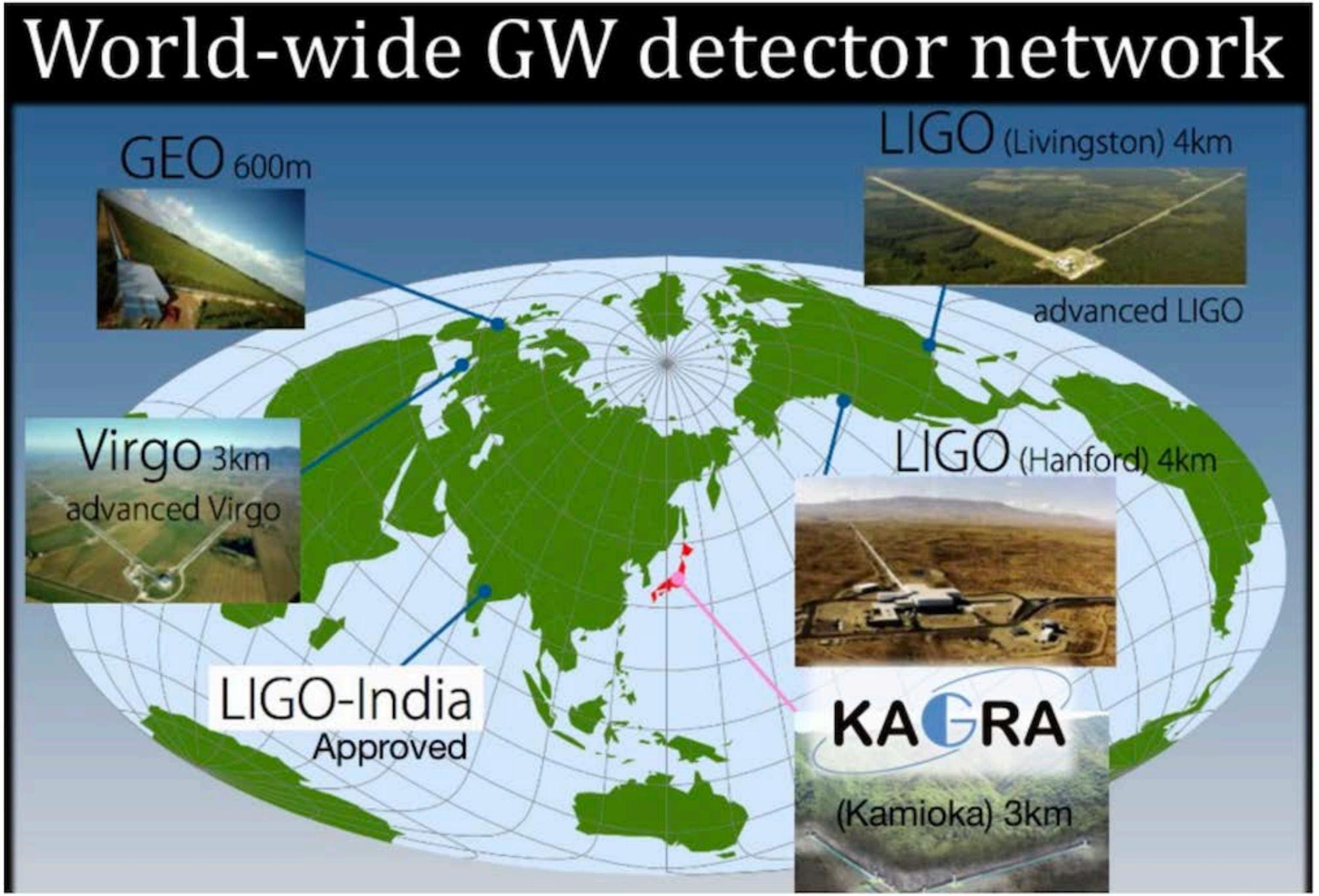
leg length fluctuation: $\Delta L \approx 4 \times 10^{-4}\,\mathrm{fm}$

**proton radius* $\approx 0.8\,\mathrm{fm}$

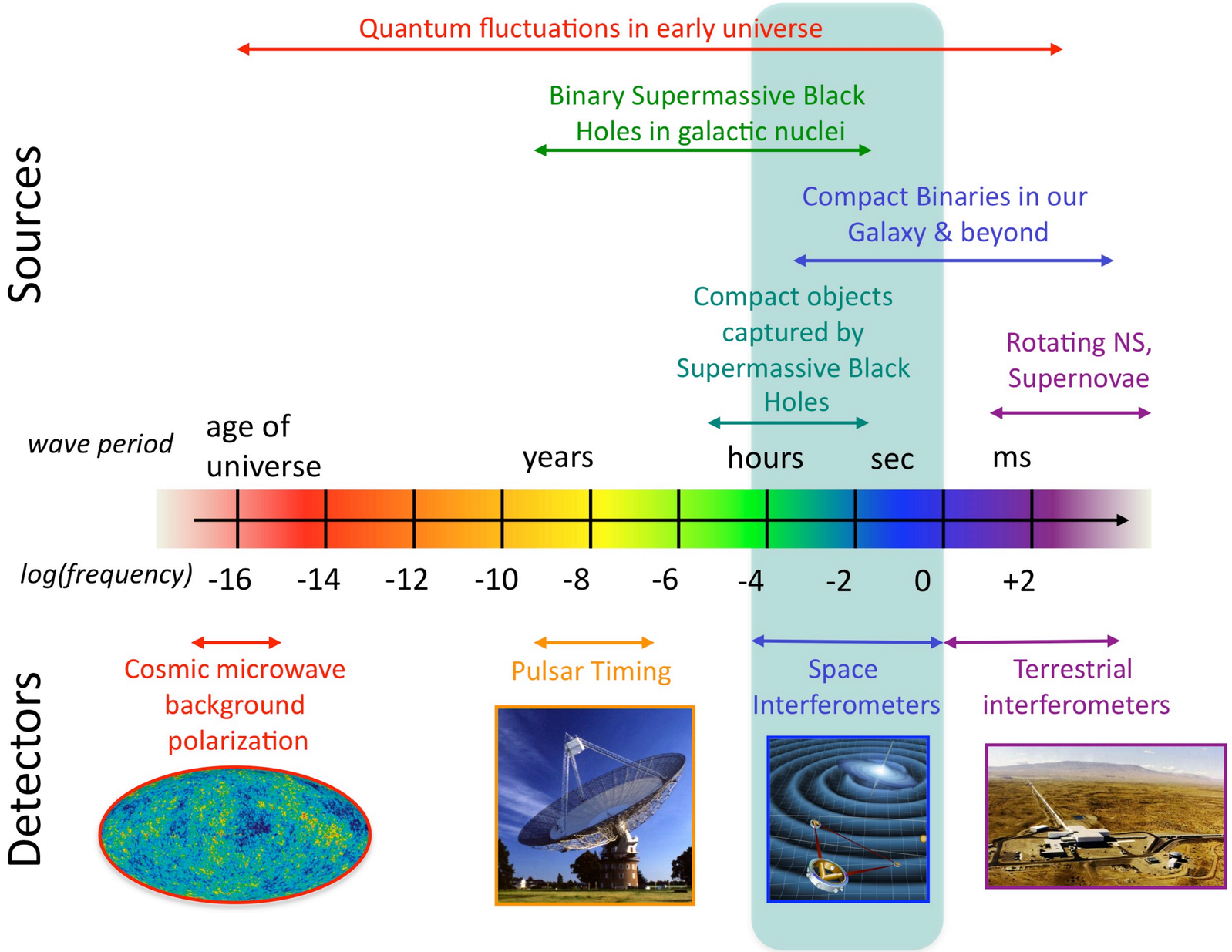
** numbers correspond to the LIGO interferometer setup*

TERRESTIAL DETECTORS

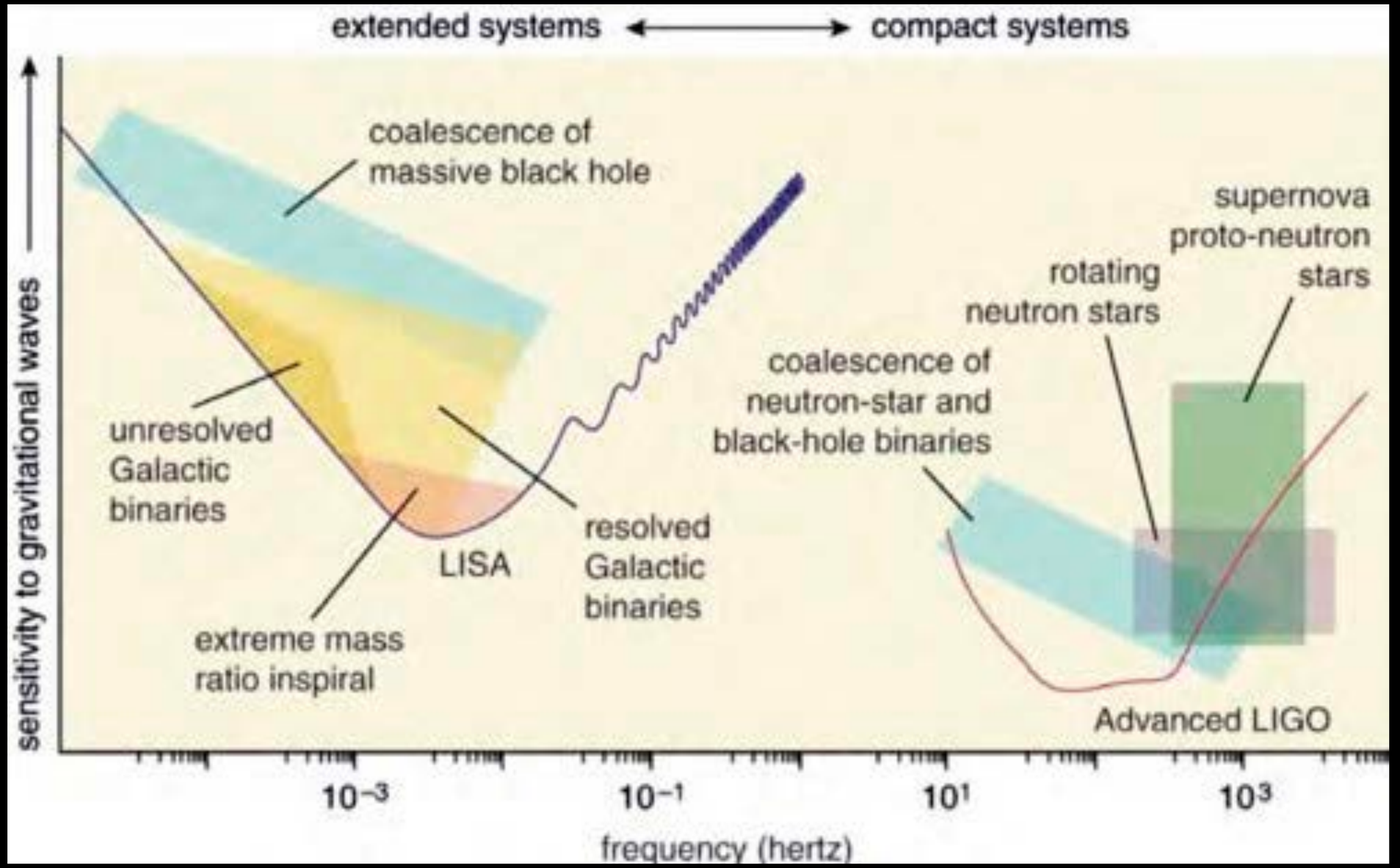
World-wide GW detector network



SOURCES OF GRAVITATIONAL WAVES



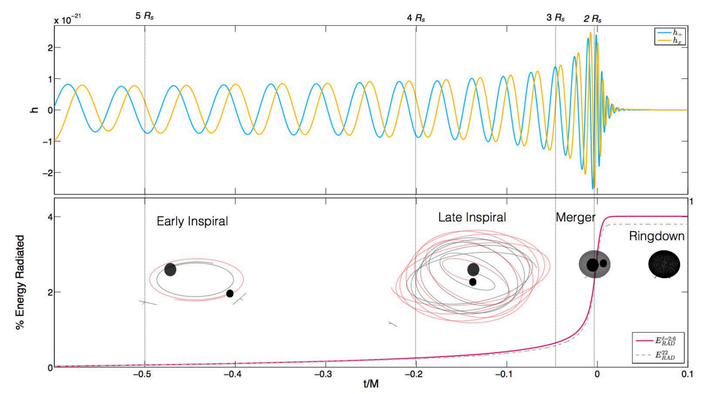
SOURCES OF GRAVITATIONAL WAVES



SOURCES OF GRAVITATIONAL WAVES

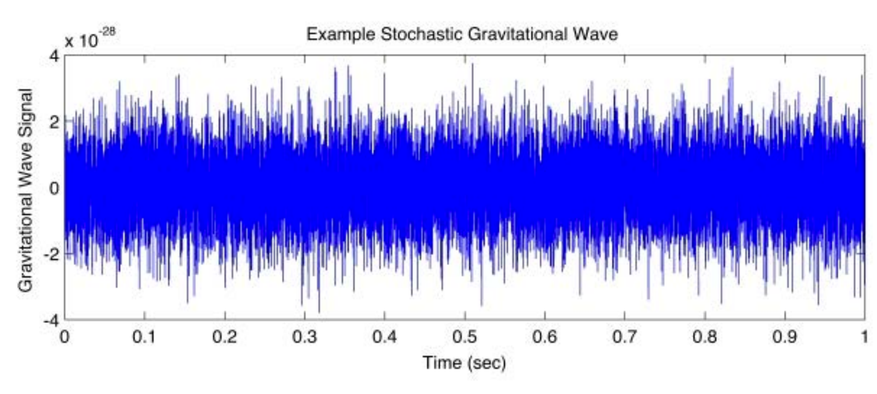
ISOLATED EVENTS

- *mergers of compact objects:*
  - solar mass black holes
  - supermassive black holes
  - neutron stars
  - exotic compact objects
- supernovae



STOCHASTIC BACKGROUNDS

- *GWs from the early universe:*
  - inflationary fluctuations
  - cosmic phase transitions
  - cosmic strings
- stochastic GWs from unresolvable binaries



Listening to the Early Universe

with

LISA

gravitational wave physics at KBFI

… and our group in the LISA consortium

KBFI's participation in the LISA consortium:

- members since 2022
- 11 members *(10 researchers + 1 PhD student)*
- contributions to working groups: Cosmology WG, Fundamental Physics WG and LISA Data Challenge WG

Current on-going projects mostly related to reconstructing GW signals from the early universe

- *"First-order phase transition SGWB in LISA: template databank, reconstruction pipeline and science interpretation"*
- *"Inflationary SGWB in LISA: template databank, reconstruction pipeline and science interpretation"*
- *"SIGWB reconstruction with LISA observations"*

→ COSMIC HISTORY

GRAVITATIONAL WAVES CAN PROPAGATE FREELY!

EARLIEST PHOTONS

10^{-32} seconds	1 second	100 seconds	380 000 years	300–500 million years	Billions of years	13.8 billion years

Beginning of the Universe

Inflation
Accelerated expansion of the Universe

Formation of light and matter

Light and matter are coupled
Dark matter evolves independently: it starts clumping and forming a web of structures

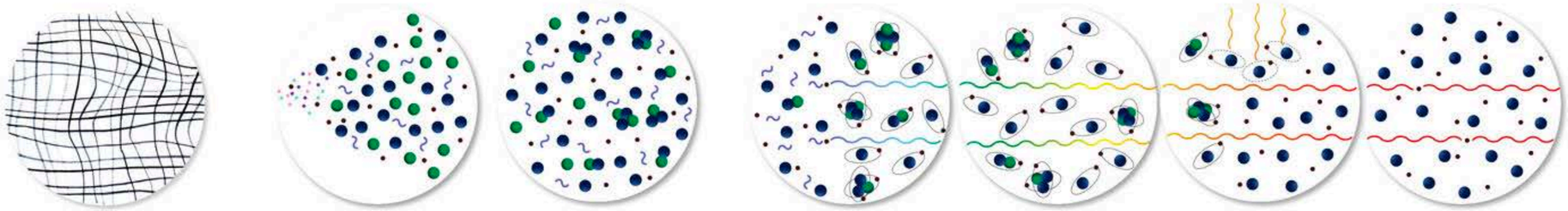
Light and matter separate
- Protons and electrons form atoms
- Light starts travelling freely: it will become the Cosmic Microwave Background (CMB)

Dark ages
Atoms start feeling the gravity of the cosmic web of dark matter

First stars
The first stars and galaxies form in the densest knots of the cosmic web

Galaxy evolution

The present Universe



- *Tiny fluctuations: the seeds of future structures*
- *Gravitational waves?*

Frequent collisions between normal matter and light

As the Universe expands, particles collide less frequently

Last scattering of light off electrons
→ Polarisation

The Universe is dark as stars and galaxies are yet to form

Light from first stars and galaxies breaks atoms apart and "reionises" the Universe

Light can interact again with electrons
→ Polarisation

cosmic phase transitons

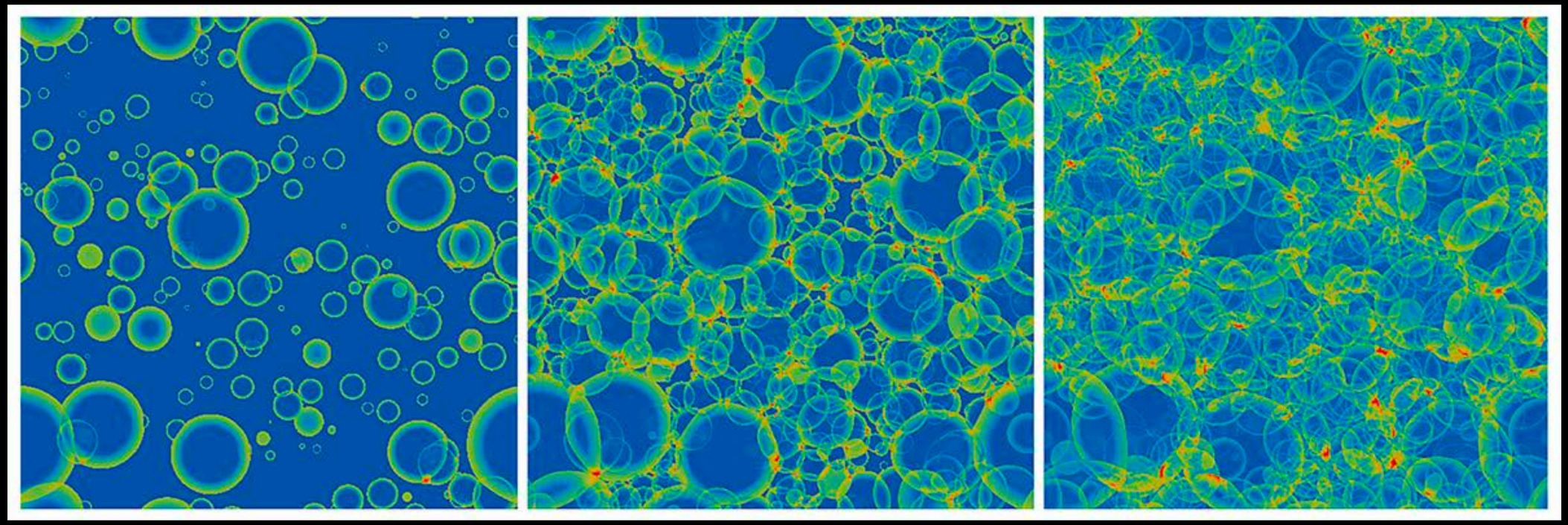
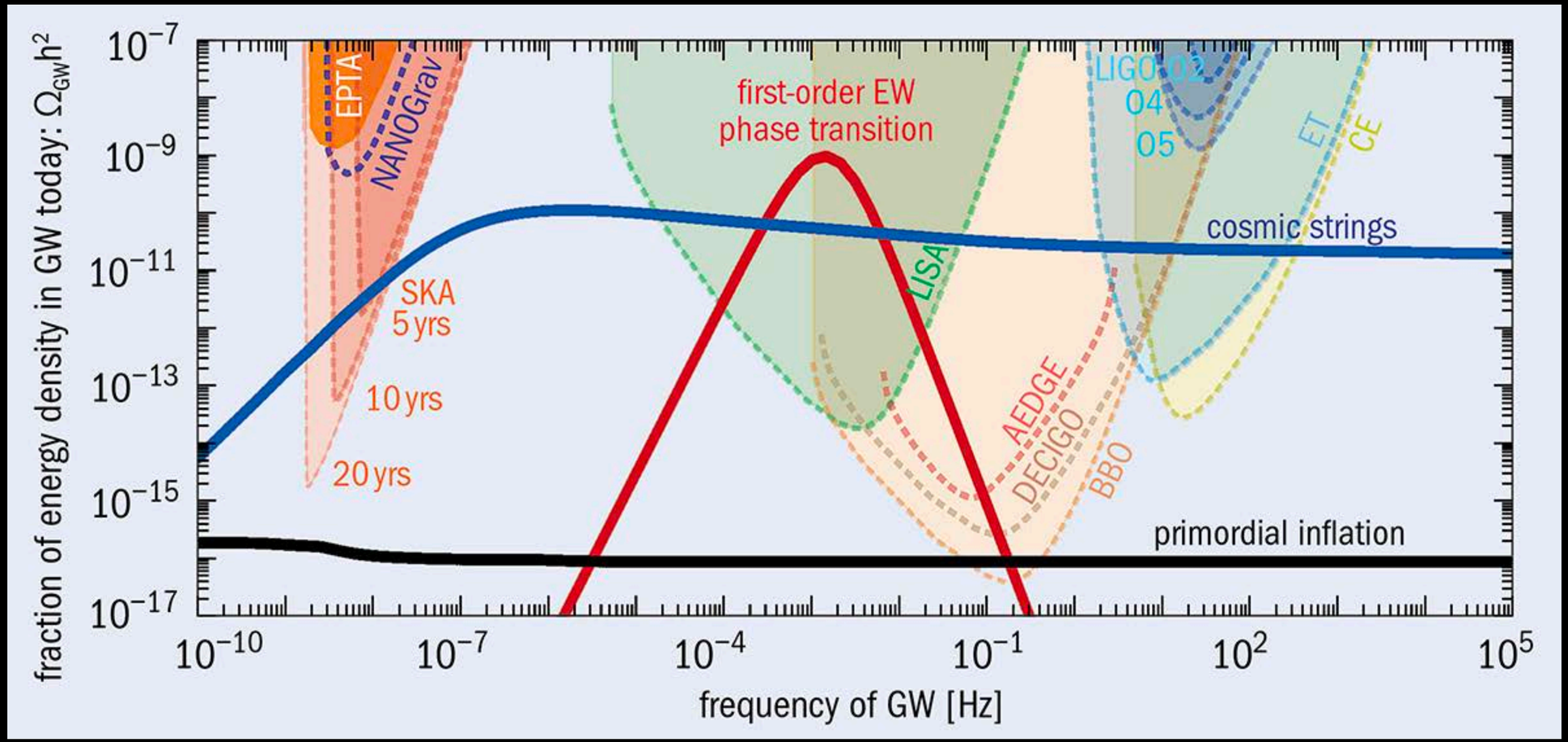


figure source: https://cerncourier.com/a/electroweak-baryogenesis/

cosmic phase transitons



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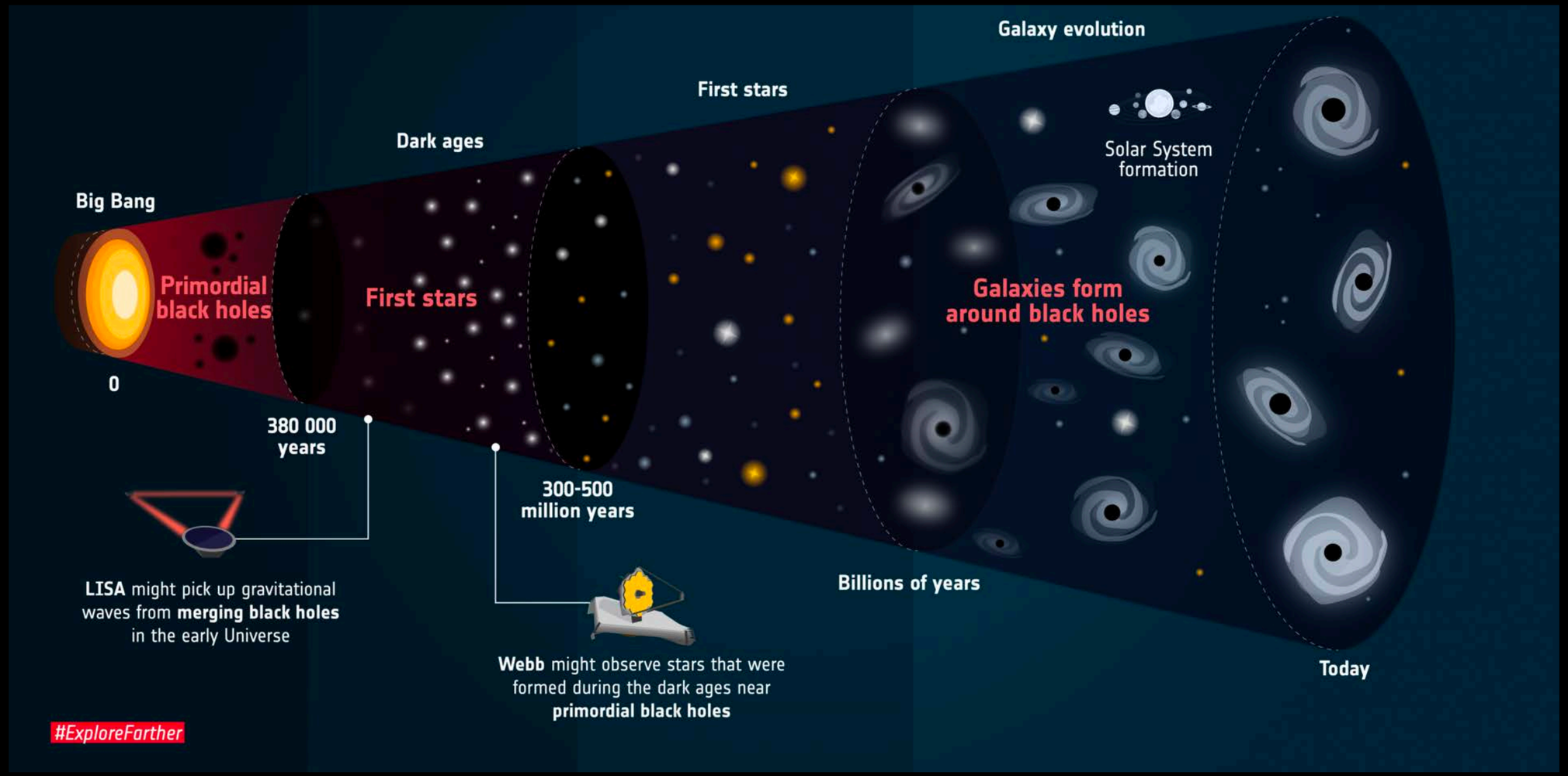
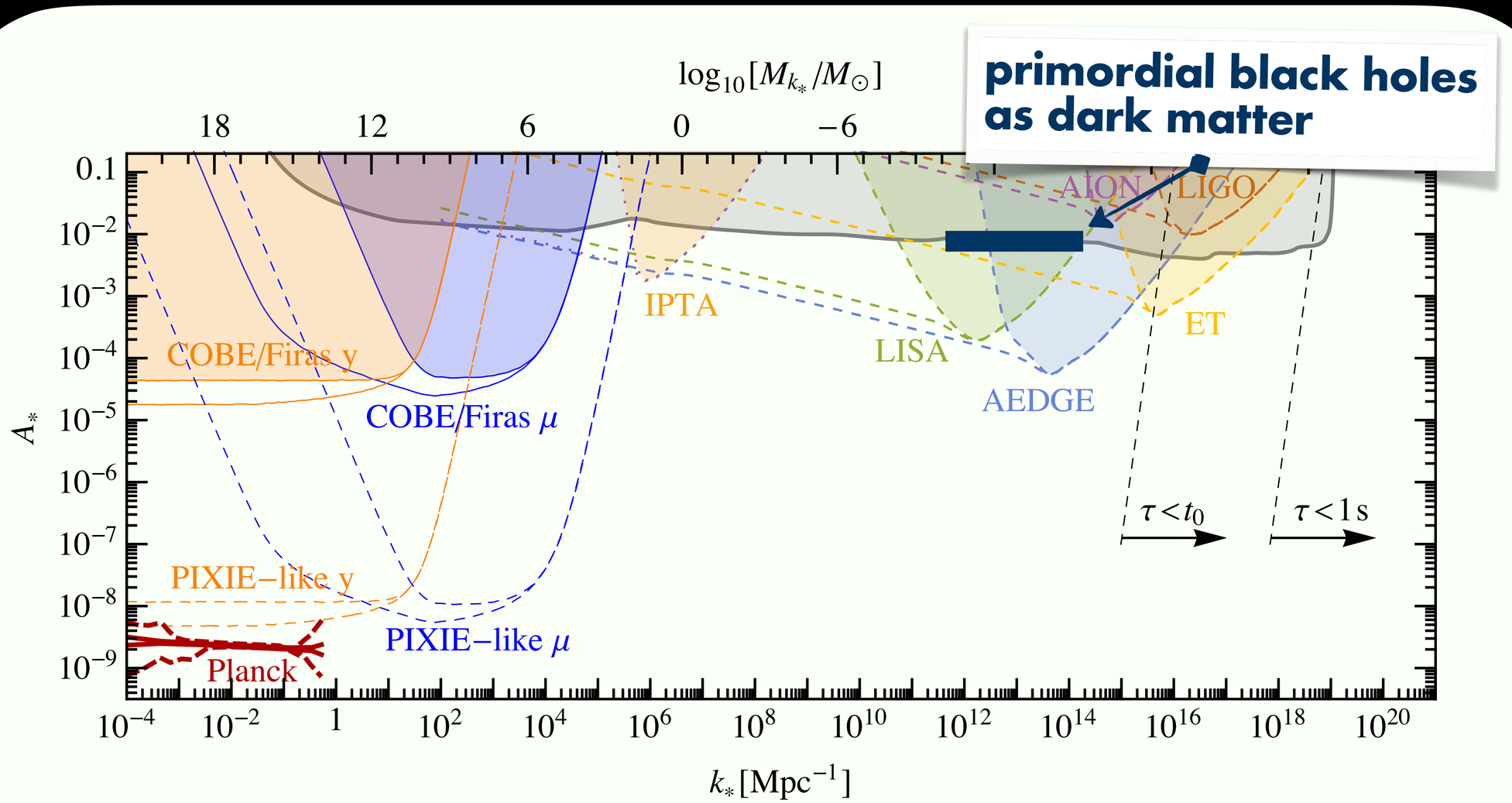
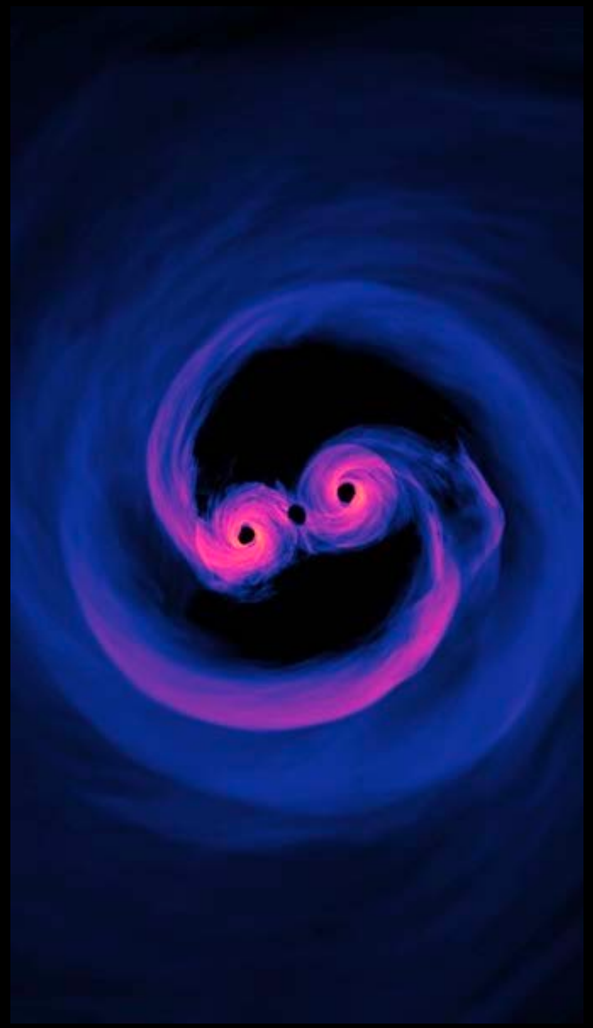
cosmic inflation and primordial black holes





LISA will test if dark matter is made of black holes!

supermassive black hole mergers



1. *supermassive black holes exist in the center of most galaxies*
2. *galaxies have been observed to merge*

→ WE SHOULD SEE MERGERS OF SUPERMASSIVE BLACK HOLES!

- billion times heavier than the sun! *HOW DID THEY GET SO LARGE?*
- probes of formation of cosmic structures and galaxies in the early universe

summary

the era of gravitational wave astronomy has just begun

oppurtunities for discovering new astrophysical objects and cosmological phenomena

if LHC claimed to recreate the conditions during the Big Bang, then LISA might hear the Big Bang!